A Combined Foam-Spray Model for Ocean Microwave Radiometry

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Abstract - **Passive microwave emissions from oceanic dispersed media are considered. The spray is modeled by the aggregates of spherical water droplets, and the foam is represented by a macroscopic system of hollow spherical water shells. Dielectric properties of foam and scattering-absorption characteristics of spray are incorporated through the boundary reflection coefficient and the radiative transfer equation. The model provides spectral band-to-band dependencies of the emission in a wide range of wavelengths from 0.3 to 8 cm for different foam-spray parameters. In particular, spray located over water or foam surfaces may cause positive as well as negative brightness temperature contrasts (the so-called "cooling effect"). At certain conditions, such sign-variable signatures can be registered by a multi-channel microwave radiometer. The modeling is intended for advanced remote sensing studies including monitoring of high wind situations, determination of air-sea fluxes and evaporation, detection of two-phase patterns in the oceans, and also for retrieval purposes**.

I. Introduction

It is a well known fact that microwave radiances from natural two-phase dispersed media such as foam, whitecap, bubbles, spray, aerosol, and also water-oil emulsions play an important role in ocean remote sensing. These remarkable phenomena have been investigated repeatedly during the last three decades; the most significant progress was reached in the evaluation of foam/whitecap microwave characteristics (e.g., [1,2,3]). In practice, however, it is difficult to distinguish microwave contributions from different dispersed objects because of their instability and microstructure variety. For example, a dense spray may increase or decrease the ocean brightness temperature by several Kelvins due to volume scattering and absorption of the microwave radiance in salt water droplets [1]. At the same time, spectral variations of the emission induced by subsurface air bubbles are relatively weak and always positive [4]. Finally, patches and streaks of stable foam can be interpreted as a quasi-blackbody with monotone spectral characteristics. To reduce uncertainties, it is necessary to invoke robust physical models since empirical approximations are not reliable enough and vague. We suppose that one option could be the development of a combined and flexible multi-parameter model, in which different types of dispersed objects are taken into account as a *radio-physical* factor unit. In this study, we propose such a model considering the following systems: "water-foam-spray," "water-spray," and "foam-spray." At Beaufort numbers > 5 - 6 similar dispersed systems cover large spaces and can exist for long periods of time in the ocean surface. Our experience shows that they can be explored perfectly using high-resolution optical and/or passive microwave techniques.

II. Spray as Radio-Physical Factor

In view of remote sensing and wave propagation theory, oceanic dispersed media can be referred to the class of volume two-phase nonuniformities located in the air-water interface. Depending on the intensity of mixing, concentration, and geometry of the phase components, such media can be described as: (I) a discrete dynamical system of particles – bubbles, droplets, suspensions, or (II) a heterogeneous macroscopic medium with randomly distributed parameters. The first model (I) is already under development and can explain microwave emission effects from stable foam, subsurface bubble populations, and also from near-surface aerosol. The second model (II) is more complicated in an electromagnetic sense; it requires correct descriptions of the macroscopic properties. However, this approach seems to be more adequate in cases of high concentrated two-phase flows, which usually are abundant in localized zones of breaking waves.

Classifications of oceanic dispersed systems including spray formations are shown in Fig. 1 (updated from [6]). There are two main mechanisms of the generation of spray [5,6,7]. The first is the injection of liquid as a result of bubble film collapses. Usually the bubble burst can produce 5 - 10 jet droplets with a radius of a few to several tens of micrometers. The second is the mechanical tearing of the wave crests by the wind. Such droplets, called "spume," have radii of 20 - 100 micrometers and more. Large droplets falling back onto the surface also produce droplets mechanically, known as "splash droplets." Injected droplets can reach a level of 8 - 15 cm over the surface; however, profiles of their concentrations may

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extend to a level that is from one to two meters. The spume droplets account for most spray volume flux, while splash droplets provide an insignificant part of the total spray volume. Spray is a source of local aerosol and affects optical properties and electromagnetic wave propagation in the ocean boundary layer. Even from these brief comments it follows that ocean spray and near-surface aerosol are important radio-physical factors. The subject of this paper is how spray may change the spectral and polarization characteristics of the ocean microwave radiance.

III. MODEL

Combined microwave models are shown in Fig. 2. The spray is represented by the aggregates of spherical water particles – droplets having certain size distributions. The foam is usually modeled by a polydispersed system of densely packed air bubbles, i.e., two-layer spherical particles with a thin water shell [1]. The brightness temperature of the system can be estimated using a solution of the radiative transfer equation (downward radiation from atmosphere is neglected)

$$T_B(\tau,\mu) = T_o\{(1-R)\exp(-\tau/\mu) + (1-\varpi)[1-\exp(-\tau/\mu)] + R(1-\varpi)[1-\exp(-\tau/\mu)]\exp(-\tau/\mu)\}, \quad (1)$$

where $\mu = \cos\theta$; $\tau = h_s\rho_s\int \pi a^2 Q_e(a)p(a)da$ is the optical thickness of spray, R is the power Fresnel reflection coefficient for a smooth surface (for two polarizations), θ is the incidence angle; $Q_e(a) = \frac{2}{x^2}\sum_{\mathrm{n}=1}^{\infty}(2\mathrm{n}+1)\,\mathrm{Re}(a_\mathrm{n}+b_\mathrm{n})$ is the dimensionless extinction factor for a single water droplet with radius a, calculated by the Mie coefficients a_n and b_n or using the Rayleigh approximation ($x = 2\pi a/\lambda$, $x \le 1$, λ is the electromagnetic wavelength); ρ_s is the number of droplets in cm^{-3}, h_s is the thickness of a spray layer, and T_0 is temperature. In (1) it is assumed that the spectral albedo of water droplets is $\varpi << 1$. The Fresnel reflection coefficient is defined for three different cases: a smooth water surface, $R = R_w$ (Fig. 2a), foam $R = R_f$ (Fig. 2b), and a plane-parallel layer of foam, located in the water surface, $R = R_{wf}$ (Fig. 2c). In the last case, this coefficient is calculated as

$$R_{wf} = \left|r_{wf}\right|^2, \qquad r_{wf} = \frac{r_{21}\exp(-2\imath\psi) + r_{32}}{r_{21}r_{32} + \exp(-2\imath\psi)}, \quad (2)$$

$$\psi = 2\pi\frac{h_f}{\lambda}\sqrt{\varepsilon_f}\cos\theta,$$

where r_{wf} is the complex reflection coefficient for a two-layer dielectric medium; r_{21} and r_{32} are the complex Fresnel reflection coefficients from the corresponding media (1- spray, 2 - foam, 3 - water), and h_f is the thickness of a foam layer. The effective complex dielectric constant of foam $\varepsilon_f(\lambda)$ may be calculated in different ways. For small bubbles ($a << \lambda$) we use a modified *Lorentz-Lorenz* formula

$$\varepsilon_f(\lambda) = \frac{1+2X(\lambda)}{1-X(\lambda)}, \quad X(\lambda) = \frac{4}{3}\pi\overline{N_f\alpha_f(\lambda)}, \quad (3)$$

$$\alpha_f(\lambda) = a^3\frac{(1-q^3)[\varepsilon_w(\lambda)-1][2\varepsilon_w(\lambda)+1]}{(1-q^3)[\varepsilon_w(\lambda)+2][2\varepsilon_w(\lambda)+1]+9q^3\varepsilon_w(\lambda)}, \quad (4)$$

$$\varepsilon_w(\lambda) = \varepsilon_\infty + \frac{\varepsilon_0-\varepsilon_\infty}{1+(\imath\frac{\lambda_0}{\lambda})^{1-\alpha}} + \imath 60\sigma\lambda,$$

where $\imath = \sqrt{-1}$, $\varepsilon_w = \varepsilon'_w + \imath\varepsilon''_w$ is the complex dielectric constant of the water (the Debye relaxation law) dependent on (t) temperature and (s) salinity; N_f is the bubble number concentration cm^{-3}; λ is the wavelength in cm; λ_0 is the relaxation wavelength; ε_0 is the low-frequency water permittivity; ε_∞ is the high-frequency water permittivity; σ is the conductivity of water; $\alpha = 0.01$ - 0.02 is the Cole-Cole parameter; α_f is the complex polarizability of a hollow spherical water shell (i.e., a single air bubble) calculated using the scattering function "forward" for a two-layer concentric sphere [8, 9]; $q = 1-\frac{\delta}{a}$ is the filling factor, a is the external radius of a single bubble, and δ is the thickness of the water shell with the complex dielectric constant $\varepsilon_w(\lambda)$. In (3) we introduce the averaged value, $\bar{x} = k\frac{\int x(a)p(a)da}{\frac{4}{3}\pi\int a^3p(a)da}$, where $p(a)$ is the normalized size distribution function for spherical particles ($k \le 0.74$ is the packing coefficient). The gamma size distribution $p(a) = \frac{1}{\beta^{\mu+1}\Gamma(\mu+1)}a^\mu\exp(-\frac{a}{\beta})$ is used for both droplets and bubbles (a is the radius in cm; pairs of constants β, μ are different for spray and foam). Formulas (3) - (4) give for foam the values $\varepsilon'_f(\lambda) = 1.2$ - 2.3 (the real part) and $\varepsilon''_f(\lambda) = 0.2$ - 0.4 (the imaginary part) that provide very high level of microwave emission at wavelengths $\lambda =$ 0.3 - 0.8 cm. Although it may appear that expressions (1) - (4) are a simple solution (for example, multiple scattering is not considered), the model, nevertheless, describes the joint influence of foam and spray on ocean microwave radiance. Indeed, electromagnetic properties of the particles, their size distributions, and volume concentrations are critical factors in the problem. Therefore, the choice and parameterization of the model have been made in accordance with real oceanographic data (e.g., [5]).

IV. Survey of Numerical Results

Examples of our numerical modeling are shown in Figs. 3 and 4. One presents polarization dependencies of the brightness temperature $T_B(\theta)$, calculated using (1), and the other demonstrates spectral dependencies of the brightness temperature contrast induced by spray only, i.e., $\Delta T_B(\lambda) = T_B(\lambda) - T_{Bw,f}(\lambda)$, where $T_{Bw,f}(\lambda)$ is the brightness temperature either of a smooth water surface ("w") or of any foam surface ("f"). These data correspond to the three listed models (Fig. 2). For these examples, the following microstructure parameters were chosen: 0.01 $< a <$ 0.2 cm ($\bar{a}$ = 0.06 cm) for spray droplets and 0.05 $< a <$ 1.2 cm ($\bar{a}$ = 0.4 cm, $\delta = 0.01$ cm) for foam bubbles.

Angular dependencies $T_B(\theta)$ for horizontal (h) and vertical (v) polarizations, as a whole, have the same form as for a water surface; however, the presence of foam leads to the smoothing of the polarization differences at the near-nadir incidence angles of $\theta = 0$ - 30°. The behavior of spectral dependencies of brightness contrast $\Delta T_B(\lambda)$ is completely different. The most important parameter here is the thickness h_f of the intermediate layer of foam (Fig. 2c). The values $\Delta T_B(\lambda)$ are defined also by foam-spray microstructure characteristics. Usually positive contrasts $\Delta T_B(\lambda) > 0$ occur when spray is located over a water surface. If spray is located over any foam surface, negative contrasts $\Delta T_B(\lambda) < 0$ can appear within the range of $\lambda = 0.3$ - 8 cm depending on the incidence angle and polarization. In this case, we observe the so-called "cooling effect" induced by spray itself. The positive contrast is a result of the absorption, and the negative contrast is a result of the scattering of microwave radiance on water droplets. Changes in the droplet size distribution affect the absolute value of $\Delta T_B(\lambda)$ mostly at millimeter wavelengths of $\lambda = 0.3$ - 0.8 cm. An important adjustable parameter is the averaged mass of liquid water in spray defined as $M = \rho_w \frac{4}{3}\pi \int a^3 p(a)da$, where ρ_w is the density of water. Obviously, microwave emission from spray and foam at millimeter wavelengths should be investigated more carefully by invoking full computations of the Mie functions (up to diffraction parameters of $x = \frac{2\pi a}{\lambda} \approx$ 2 - 3) and multiple scattering terms in a radiative transfer equation. Note that sign-variable microwave signatures from spray are damped slightly due to strong emission from foam.

V. Summary

A numerical modeling of microwave emission contributions from oceanic dispersed systems has been developed. It was shown how spectral and polarization characteristics of the emission may depend on microstructure parameters and the type of dispersed systems. One important result is the illumination of the so-called "cooling effect" due to the influence of spray located over a foam surface. In general, negative brightness contrasts ("cooling") are associated with scattering, and positive brightness contrasts ("warming") are associated with absorption of electromagnetic waves on water droplets. Such sign-variable signatures are unusual attributes of ocean microwave emission fields and, therefore, they can be recognized easily using a sensitive radiometer. The basic model, however, may be improved through the incorporation of vertical effective profiles and fluctuations of microstructure parameters. Also it is necessary to include atmospheric effects that may change spectral dependencies of brightness contrasts induced by spray. Combined radio-physical models related to oceanic two-phase turbulent flows would be more adequate and versatile especially for high-resolution passive microwave imagery.

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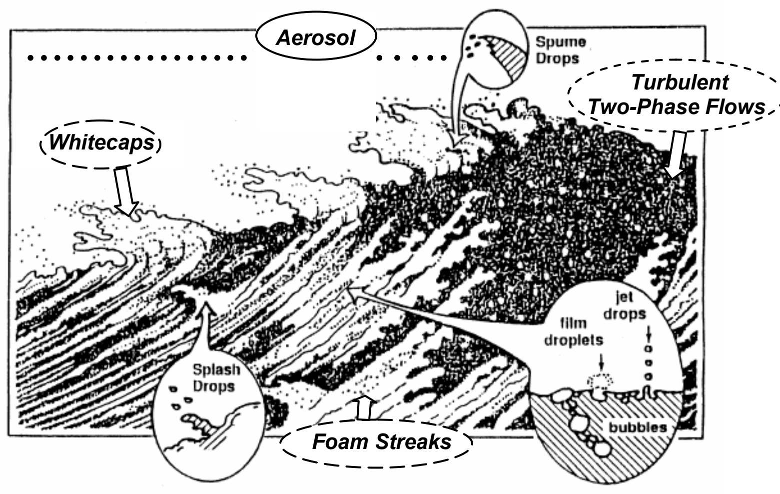


Figure 1. Classifications of oceanic dispersed media for remote sensing.

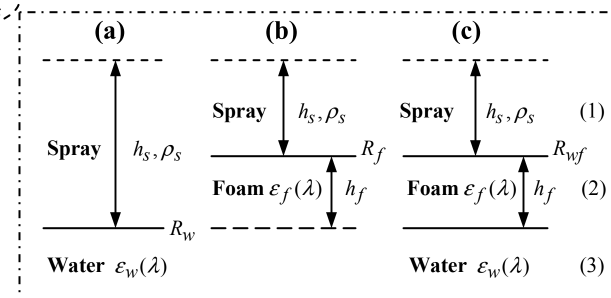
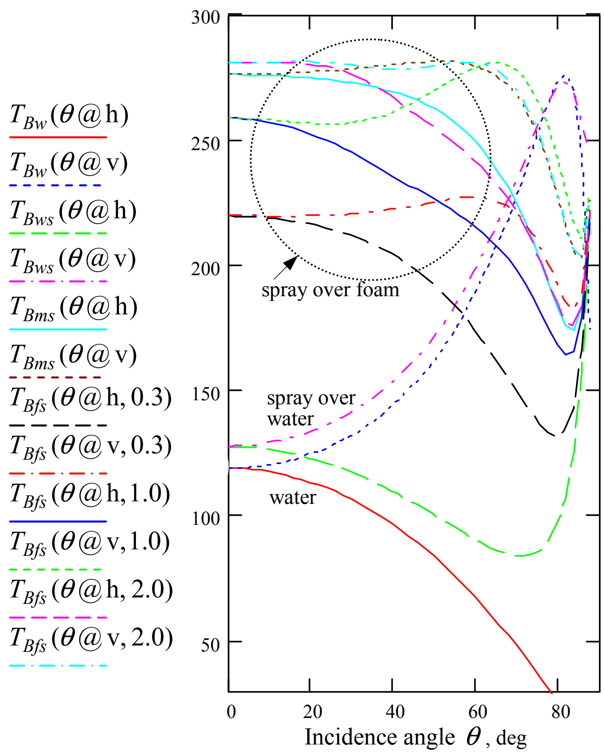


Figure 2. Microwave models:
(a) "water-spray," (b) "foam-spray," (c) "water-foam-spray."



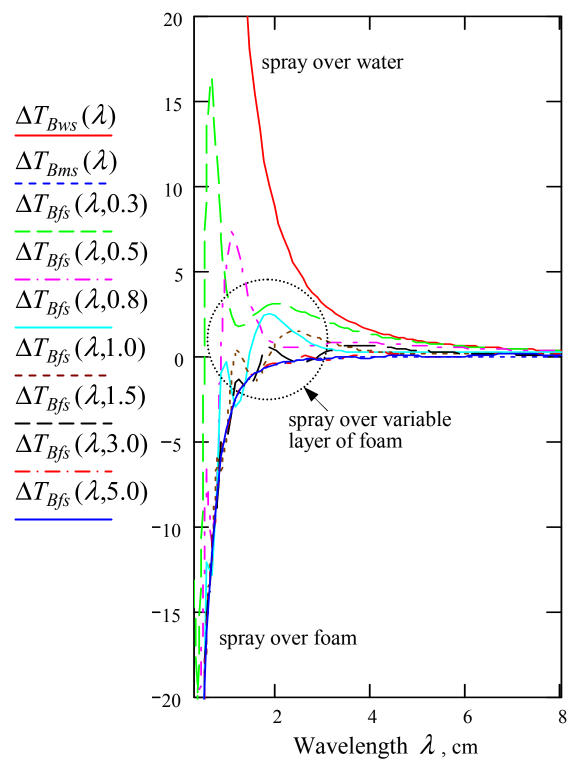


Figure 3 (left). Brightness temperature $T_B(\theta)$ calculated for foam-spray systems (Fig. 2) at horizontal (@h) and vertical (@v) polarizations. T_{Bw} - water; T_{Bws} - (a) model; T_{Bms} - (b) model; $T_{Bfs}(h_f)$ - (c) model with variable thickness of foam layer: $h_f = 0.3, 1.0, 2.0$ cm. $\lambda = 2$ cm.

Figure 4 (right). Spectral dependencies of brightness temperature contrast $\Delta T_B(\lambda)$ induced by spray (at nadir $\theta = 0$).

ΔT_{Bws} - (a) model; ΔT_{Bms} - (b) model; $\Delta T_{Bfs}(h_f)$ - (c) model with variable layer of foam: $h_f = 0.3, 0.5, 0.8, 1.0, 1.5, 3.0, 5.0$ cm.

$t = 10$°C, $s = 35$ ppt. $\beta = 0.015$ and $\mu = 3$ for spray; $\beta = 0.1$ and $\mu = 5$ for foam. $h_s = 10$ cm, $M \sim 10^{-3}\, g/cm^3$.